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An Internal Charging Environmental Specification for Geosynchronous and HEO/Molniya Satellites

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Internal charging has been indicated as the cause of many satellite anomalies. In some cases, it has been argued that internal charging has caused satellite system failures. An internal charging environment specification is needed by satellite manufacturers for setting design requirements. A specification is also required for providing energetic electron flux levels and total fluence levels for electron beam testing to verify that critical systems are immune to internal charging, for performing tests on subsystems, and for use in anomaly investigation programs. We present preliminary internal charging environment specifications that have been developed for some commonly used orbits such as geosynchronous and Molniya or high Earth orbits (HEO) and show what they predict as shielding requirements to reduce worst-case electron fluxes to safe levels.

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1. Introduction

There has been much speculation and concern in the science and engineering community about whether satellites are damaged because of internal charging.[1,2] Several authors have discussed the possibility of charging of the interior of subsystems and cabling by high-energy electrons capable of penetrating the outer skin of satellites, cable jacketing, and thick dielectrics.[3,11,12,15] The CRRES environmental observations combined with in-situ energetic electron observations from other satellites has given the space radiation environment community a better picture of the causes of internal charging. This has been combined with the CRRES engineering measurements of internal charging and discharges[6,7,14] to arrive at a better understanding of the process.

Solar wind high-speed streams often arrive at Earth under interplanetary magnetic conditions that cause the energy in the stream to be efficiently coupled into the radiation belts.[4,9] From the charging perspective, this shows up as a significant enhancement, for days, in the penetrating electron fluxes. These enhancements are well above the levels contained in the radiation belt models (e.g., NASA AE8) used to calculate radiation dose. The long-term average penetrating electron flux is in fair agreement with the models. However, during the periods of flux enhancement, the increased fluxes are often sufficient to charge items such as signal cables, electronic boards, dielectric structures, ungrounded spot shields on microelectronic devices, etc.[11,12] These enhanced penetrating electron fluxes are not just a simple increase of the standard model environments because the spectral shape is different. If the grounded passive shielding protecting critical items is sufficiently thin, the items can charge up to dielectric breakdown levels during the period of enhanced fluxes and generate ESD signals on data lines and device inputs. It is this ESD possibility and its elimination via careful system design that is of concern here.

To eliminate internal charging requires that one either choose materials that can bleed off buried charge to ground or properly shield susceptible systems and subsystems. For example, if circuit board materials, wiring insulation, piece-part shields, dielectric structures, etc. have connections to ground, via paths that have conductivity sufficient to bleed off deposition currents, then internal charging will not be a problem. Otherwise, the systems need grounded passive shielding to reduce the charging environment to acceptable levels.

What are the worst-case fluxes that one has to protect space systems against? This is a two-fold question. (1) What are the worst-case fluxes; and (2) what is the total fluence that must be tolerated? All materials have a finite resistivity so it becomes a question of balance between the rate of charge deposition and the rate charge is bled to ground such that the materials do not reach breakdown electric fields. This allows for limited charging to occur over short intervals (few hours) as long as the finite resistivity keeps the electric fields below arcing levels. It should be noted that the specification sheets for many materials such as PTFE (Teflon) composites claim resistivities of order 10^{13}–10^{14} ohm-cm, yet they are observed to store charge for a long time in vacuum and have been known to show an effective resistance of 10^{15}–10^{17} ohm-cm. Such materials will charge to breakdown levels when exposed to pA/cm^2 or sub-pA/cm^2 levels of particle current. (A word of caution here: it is best to measure the conductivities of materials for space applications in vacuum, especially if the conductivities are very low. Also, surface effects, processing, and handling can change effective conductivities.)

The data available on the occurrence of internal charging and dielectric breakdown in the space environment come from the CRRES charging experiment.[6,14] The in-situ data from this experiment indicated that electron fluxes of 10^5 electrons/(cm^2 s) lasting ~10 h were at the threshold for onset of arc discharges.[7] This "safe" flux level was based on requiring that no discharges be observed during a full CRRES orbit (10 h) where the total electron fluence that could penetrate the experiment shielding ($E_e > 300$ keV) was measured. Frederickson et al.[7] established this "safe level" by reducing the required electron flux to 1/5 the actual levels at which discharge onset occurred. This was done because they could not be certain that their measurement geometries and materials represented all possible configurations nor that other configurations or materials might suffer ESD at lower fluence levels.

In what follows, we have assumed that 10^5 electrons/(cm^2 s) is the long-term average (10 h) criteria for a "safe level" at which internal charging will not produce arcs. Using this criteria, one can examine the average flux levels that are observed in different orbits and determine the shielding required, if any, to make space systems immune or tolerant to internal charging. Again, we emphasize that the results are for "typical" materials as described in Ref. 7. New materials should be tested in their expected space flight configurations to determine whether they will charge and arc and at what electron flux levels. Below, we discuss the observations of "worst-case" electron flux levels and use the observed fluxes to provide a internal charging environment specification for two often-used orbits. These are the geosynchronous (GEO) and highly inclined high Earth orbit (HEO) or Molniya orbit. The HEO/Molniya orbits have 12-h periods with apogees near 40,000 km and inclinations near 63° such that the apogee "hangs" at two fixed longitudes. The GEO and HEO/Molniya orbits are often used for communication satellites.

2. Flux Measurements

To help find the worst-case environments, we examined the daily average >2 MeV electron fluxes measured on the GOES satellites during the January 1986 through July 1998 period. The times of the peaks in the GOES >2 MeV electron fluxes were used to focus the examination of other datasets such as the Los Alamos National Laboratory's (LANL) geosynchronous and GPS satellite data plus CRRES data.[13]

2.1 GEO Worst-Case Environment

The worst-case GOES energetic electron fluxes occurred following the March 24, 1991 magnetic storm event. This was also the period of worst-case fluxes for the CRRES satellite, which covered essentially all L's < 7 (L is the geocentric distance to the magnetic equatorial crossing point of a geomagnetic field line in units of earth radii; 6378.14 km = 1 R_E.) Data for March 28, 1991 from the CRRES, GOES, and LANL energetic electron fluxes at L ~ 6.6 were combined to construct a worst-case average spectrum as shown in Figure 1. The fluxes used were daily average fluxes. The different satellite data are identified in the Figure 1 legend. The logarithm of the spectrum can be accurately fit by $2.34 \times e^{-1.57E_e}$.

As noted above, the CRRES internal charging specification was based on a 10-h average flux. To determine whether there was a strong relationship between the average flux obtained and the averaging interval used, the worst-case average fluxes from the GOES-7 data were obtained for different averaging intervals over a two-week period centered on March 28, 1991. The resultant worst-case average flux versus averaging interval data are shown in Figure 2. As can be seen, the worst-case flux did not depend strongly on the duration of the averaging interval for intervals ≤1 day. This result has been used to define beam testing levels in conjunction with Figure 1.

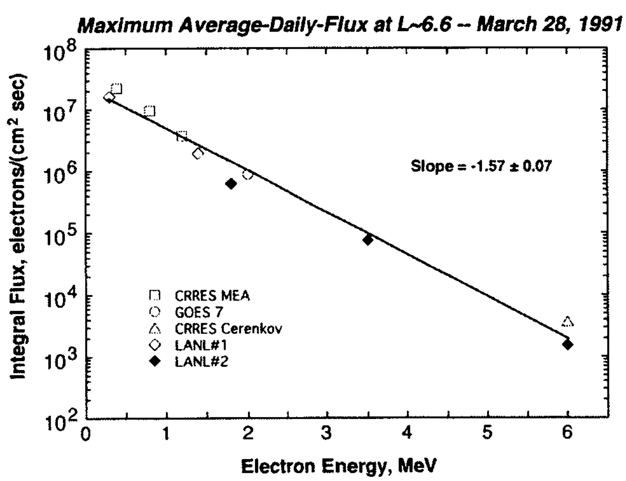

Figure 1. Omnidirectional integral flux spectrum for GEO internal charging environment.

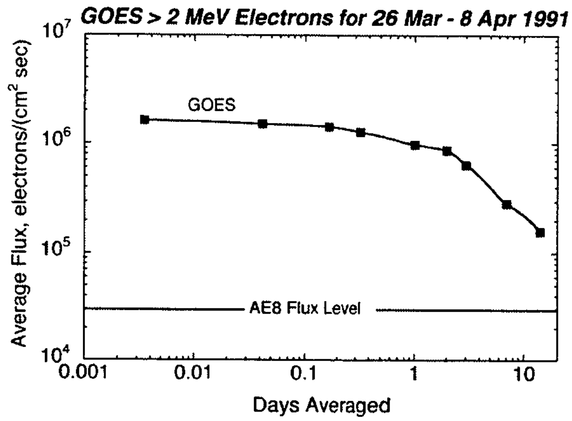

Figure 2. Maximum average GOES > 2 MeV omnidirectional flux vs averaging interval duration.

2.2 HEO/Molniya Worst-Case Environment

The generation of an average worst-case electron spectrum for the HEO/Molniya orbit is more complicated than for GEO orbit. Data is not readily available throughout the HEO/Molniya orbit. However, data was available for L ~ 4 from CRRES, GPS, and HEO satellites. The worst-case fluxes were obtained for L ~ 4 from these satellites and compared. The CRRES and GPS data were taken at the magnetic equator and had to be "mapped" to the magnetic latitude of the HEO satellite. The mapping required assuming a shape for the energetic electron pitch angle distributions. These were assumed to be $\propto \mathrm{Sin}^2\alpha_0$ after Vampola.[13] The mapped CRRES and GPS worst-case fluxes agreed well with the HEO worst-case fluxes (not shown) even though each satellite experienced its worst-case flux at L ~ 4 during different periods (April 1994, March 1991, and April 1984 for HEO, CRRES, and GPS, respectively). The good agreement between these different datasets at L ~ 4 provided some confidence that we could use the CRRES worst-case fluxes throughout its L range to specify the worst-case flux for the HEO/Molniya orbit.

First, the CRRES worst-case fluxes were obtained at different L values and used to generate a radial profile at different electron energies. As is shown in Figure 3, the radial profiles could be fit by a simple functional form with the same shape for a range of electron energies. Similarly, the electron spectra were formed at different L values to examine the L dependence of the spectra. As is shown in Figure 4, the spectra at different L values were very similar. A single spectral shape could be used to approximate the spectra at all L values by performing a weighted fit to the combined spectral points from the L's shown in Figure 4. The weights applied were in proportion to the time spent by CRRES in each L range.

The radial dependence of the fluxes shown in Figure 3 and the average spectral shape shown in Figure 4 were used to estimate the worst-case average electron flux that would be experienced by an HEO/Molniya satellite as it traversed its orbit. To do this required mapping these CRRES equatorial data to the proper latitudes on a point-by-point basis along the HEO/Molniya orbital trajectory. Again, as discussed above, the equatorial pitch angle distributions were assumed to be of the form $\mathrm{Sin}^2\,\alpha_0$.

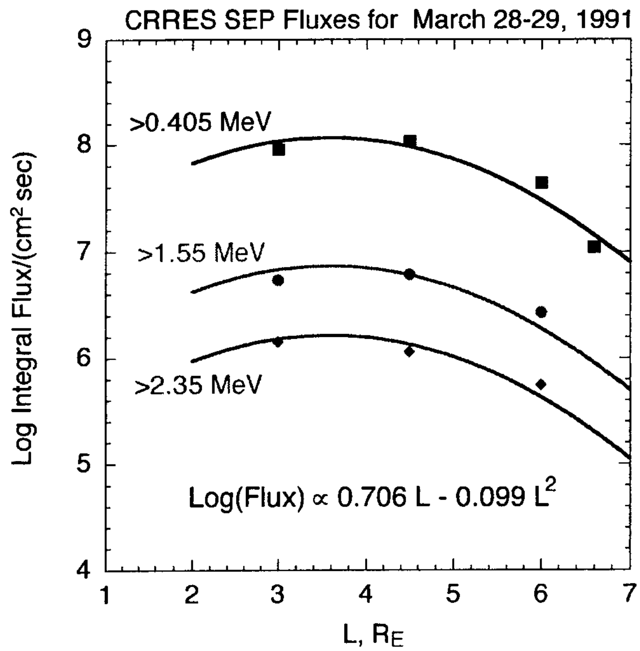

Figure 3. Radial profile of energetic electron fluxes taken at the magnetic equator during March 28-29, 1991.

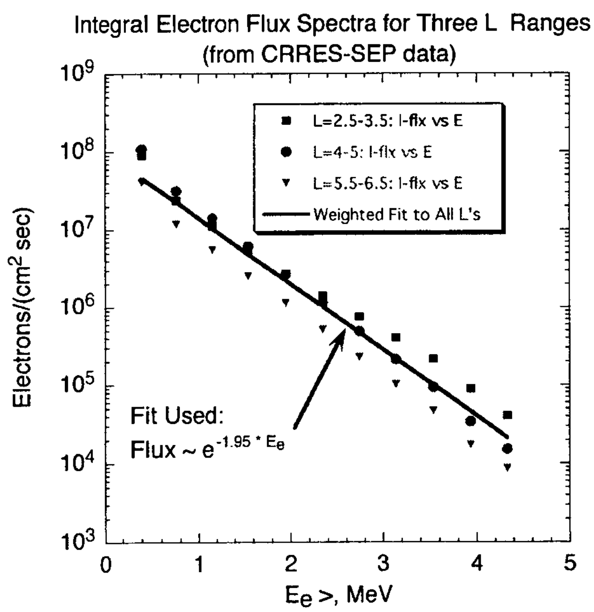

Figure 4. Worst-case CRRES electron spectra for different L ranges. The straight line is a weighted exponential fit to the combined spectra with the weights being proportional to the time spent in each L range.

The Tsyganenko 1996 magnetic field model[10] was used to compute the nominal HEO/Molniya L and magnetic latitude (λ) for a typical orbit. The resultant L and λ history are shown in Figure 5. The λ was used to obtain the equivalent equatorial pitch angles, α_0, using the dipolar relationship:

$$\mathrm{Sin}^2\alpha_0 = \mathrm{Cos}^6\lambda/(1 + 3\mathrm{Sin}^2\lambda)^{1/2}.$$

A ten-hour period, centered on perigee, was used to calculate the orbit averaged electron flux for several energies. The resultant average integral spectrum is shown in Figure 6. For comparison, the "safe" ten-hour averaged flux level that was derived from the CRRES charging data is also shown. We note that electrons with energies $E_e \leq 2.8$ MeV exceed the "safe" flux level. Also, the average spectrum can be represented by an exponential form as shown in Figure 6.

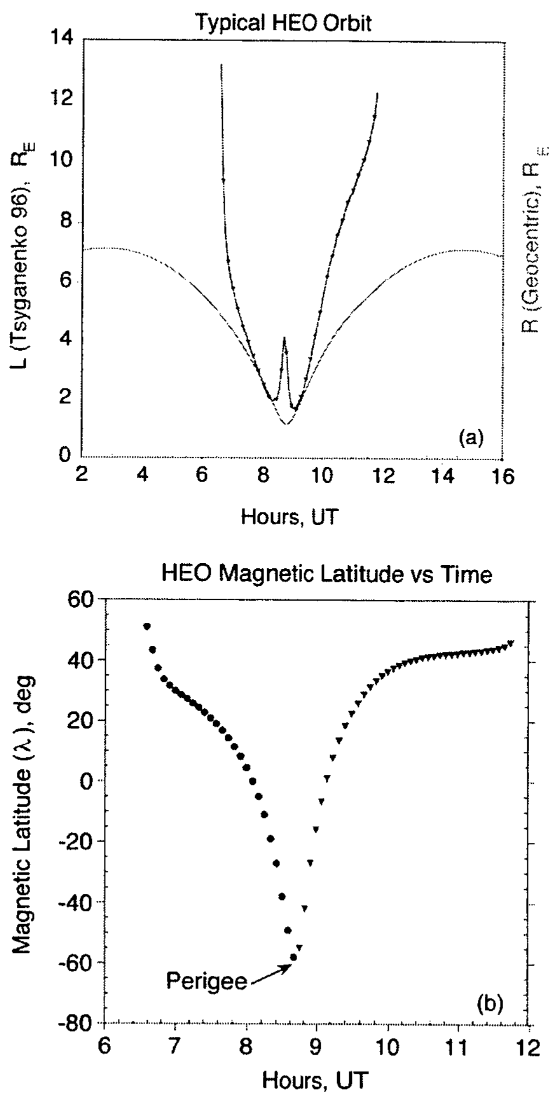

Figure 5. A typical HEO/Molniya orbit showing radial position (R) and L value (panel (a)) plus the magnetic latitude (panel (b)) versus time. Perigee is near 0845 UT.

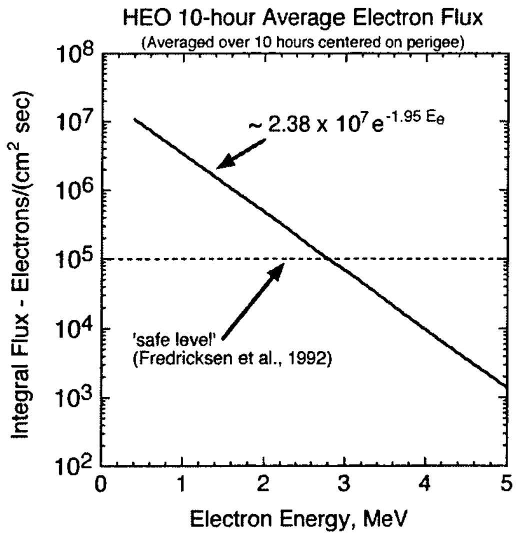

Figure 6. Worst-case 10-h average integral electron flux for the HEO/Molniya orbit.

Finally, the GEO and HEO/Molniya worst-case average spectra, shown in Figures 1 and 6, respectively, were used to calculate the shielding necessary to keep the electron flux levels interior to satellites and their subsystems at "safe" levels. These spectra were used in a particle transport code (EGS4, see Ref. 8) to calculate the resultant average electron flux that would be expected behind shielding. The results of the calculation are shown in Figure 7 for flat-plate shielding. The calculations show that it takes approximately 145 mils and 125 mils of aluminum shielding to reduce the worst-case average fluxes for GEO and HEO/Molniya orbits, respectively, to the "safe" level of 10^5 electrons/(cm^2 s).

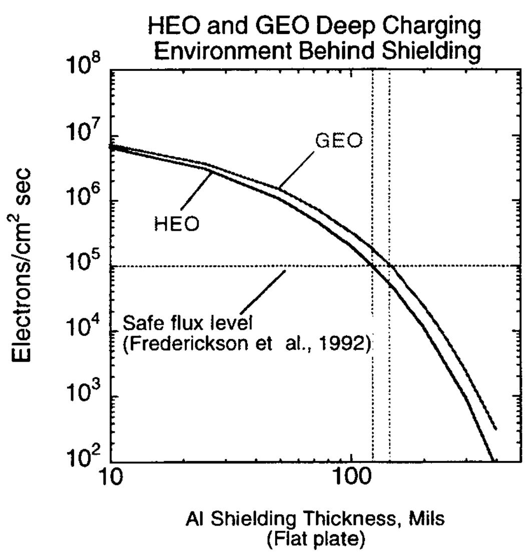

Figure 7. Electron flux behind shielding for the GEO and HEO/Molniya internal charging environments of Figs. 1 and 6.

3. Discussion

The generation of the geosynchronous internal charging average spectrum was straight forward. The only question would be how often such levels might be attained by the environment. The present available observations indicate that these levels are probably reached once or twice every solar cycle, with several other storm periods reaching levels just below these worst-case levels.

Whether these flux levels (Fig. 1) are of concern or not depends, as was mentioned above, on the exact materials used in the satellite construction and the sensitivity of the electronics to electrostatic discharge (ESD) voltages and currents. If the systems are not shielded they would have to be designed to withstand the ESD "signals" or be designed to suppress them by using materials that dissipate the charge before it reaches critical electric field breakdown levels.

The generation of the HEO/Molniya internal charging specification, given in Figure 6, was more complicated. It required reliance on data taken by the CRRES satellite near the magnetic equator. It is clear that CRRES did capture a worst-case energetic electron event that lasted more than a day. The highly elliptical near-equatorial orbit of CRRES, with its low perigee and high apogee, provides a good reference dataset for constructing a internal charging environment on L's below and in the neighborhood of the geosynchronous orbit. The mapping of the CRRES data to the HEO/Molniya orbit required some simple but critical assumptions. The primary assumption was that the energetic electron equatorial pitch angle distribution could be represented by a function of form of $\mathrm{Sin}^2\,\alpha_0$. This form was observed in the CRRES data[13] but during relatively quiet conditions. There are recent Polar and SAMPEX satellite observations of > 1.5 MeV electron fluxes that show that the angular distributions can be nearly isotropic[5] during enhanced flux intervals of the type used to obtain the worst-case average fluxes above. Given these recent observations, one might argue that our use of $\mathrm{Sin}^2\,\alpha_0$ for mapping the CRRES data to the HEO/Molniya latitudes underestimates the fluxes there. So far, the Polar and SAMPEX comparisons have been made for only a limited number of L values. It needs to be shown that the electron fluxes are isotropic over a wide range of L during the enhanced flux intervals before we would consider increasing the fluxes that make up the HEO/Molniya internal charging specification spectrum of Figure 6.

We would argue that the GEO and HEO/Molniya internal charging specification spectra given in Figures 1 and 6 should be used as the reference environments for design of systems flying in those orbits. Also, the "safe" level of 10^5 electrons/(cm^2 s) should be the maximum flux allowed inside satellite systems and subsystems based on these environments. This is especially true for the cases where testing was not done on materials and subsystems to show that they will not charge or that they could withstand the ESD generated by internal charging.

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